

Plant Fibers and Bio-Based Materials for Sustainable Spacesuit Design: A Critical Review from Plant Biodiversity to Space

Praxedes Jeanpierre Merino-Ramirez ^{1,2,*}, Nayeli Yamile Farfan-Carhuamaca ³, Sheila Jacqueline Principe-Merino ³, Iris Oliveira da Silva ^{1,2,*} and Rebeca Salvador-Reyes ^{3,*}

¹ Programa de Pós-Graduação em Engenharia Têxtil (PPgET), Centro de Tecnologia, Universidade Federal do Rio Grande do Norte, Natal 59078-900, RN, Brazil

² Grupo de Pesquisa em Materiais Têxteis Avançados (GPMAT), Universidade Federal do Rio Grande do Norte, Natal 59078-900, RN, Brazil

³ Facultad de Ingeniería, Universidad Tecnológica del Perú, Lima 150101, Peru; u20216892@utp.edu.pe (N.Y.F.-C.); u23247543@utp.edu.pe (S.J.P.-M.)

* Correspondence: praxedes.merino.129@ufrn.edu.br (P.J.M.-R.); iris.oliveira@ufrn.br (I.O.d.S.); rsalvador@utp.edu.pe (R.S.-R.)

Abstract

Human space exploration requires low-mass textiles with high mechanical strength, thermal stability, durability, and protection against extreme environmental conditions. This critical narrative review evaluates the potential of plant biodiversity as a source of fibers, biomaterials, and bioinspired structures for sustainable space textile materials based on scientific literature retrieved from Scopus and Web of Science, complemented by technical information from the NASA Technical Reports Server. The reported maximum tensile strengths of individual flax, hemp, ramie, bamboo, and banana fibers reach 1830, 1110, 938, 800, and 914 MPa, respectively. However, these literature maxima should not be interpreted as allowable for aerospace design because plant-fiber properties exhibit substantial variability and require statistically based validation at the textile and component levels. Beyond structural applications, natural cellulosic and lignocellulosic fibers may also offer advantages for textile physiological functions, including moisture management and skin-contact comfort, although these attributes require validation under space-specific conditions. Nanocellulose and porous cellulosic materials show potential for insulation, membranes, and coatings, with thermal conductivities of $\leq 20 \text{ mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Amazonian species, such as *Attalea speciosa*, *Mauritia flexuosa*, *Manicaria saccifera*, *Euterpe oleracea*, and *Copernicia prunifera*, exhibit promising properties for bio-based applications. However, moisture, radiation, abrasion, structural variability, thermal stability, and extraterrestrial dust remain key limitations, with no evidence of plant-derived fibers in operational EVA spacesuits. Surface modification can tailor wettability, interfacial compatibility, and stability. Their near-term use may focus on secondary and multifunctional components, whereas their long-term sustainability depends on modularity, repairability, material recovery, and in-space manufacturing. This perspective distinguishes the potential of EVA systems from their established use in IVA crew clothing.

Keywords: plant biodiversity; lignocellulosic fibers; nanocellulose; bio-based materials; spacesuits; extravehicular mobility unit (EMU); extravehicular activity (EVA); intravehicular activity (IVA)

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1. Introduction

Human space exploration requires materials capable of ensuring protection and performance under extreme environmental conditions, where low mass, mechanical strength, thermal stability, and durability are critical. In this context, the spacesuit constitutes a complex multifunctional textile system that may incorporate up to 16 layers designed for pressurization, thermal control, oxygen retention, dust, abrasion, and impact protection [1,2]. The current systems combine high-performance materials such as nylon, Nomex, Kevlar, Dacron, polyurethane, and aluminized Mylar [3]. The development of sustainable alternatives remains a major challenge, as new materials must simultaneously meet stringent safety, performance, and reliability requirements.

In this context, plant biodiversity represents a diverse source of fibers and lignocellulosic components with potential for lightweight and multifunctional materials [4]. In addition to their use as reinforcement phases in biocomposites, natural cellulosic and lignocellulosic fibers have also been used in textile structures worn close to the skin, where their hygroscopicity, moisture absorption, and moisture-transfer characteristics can contribute to thermophysiological comfort and moisture management [5,6]. Fibers such as flax, hemp, ramie, sisal, jute, and bamboo exhibit low density and specific mechanical properties that favor their application in engineering biocomposites [7,8]. Although surface treatments and nanoengineering strategies can improve the stability and interfacial interaction of polymer matrices, their application in highly demanding technological environments is still constrained by moisture sensitivity, structural variability, thermal instability, durability, and quality control [8,9].

To mitigate these limitations, lignocellulosic fibers can be subjected to surface engineering and refining strategies designed to regulate their chemical reactivity, polarity, wettability, and morphology before incorporation into a composite. Their hierarchical structure is primarily composed of cellulose embedded within a matrix containing hemicellulose and lignin, whose relative proportions and distribution influence surface chemistry, moisture sensitivity, and interfacial behavior [10,11]. Chemical treatments, such as alkaline mercerization, silanization, acetylation, benzylation, peroxide or permanganate oxidation, and coupling-agent modification, can remove or redistribute non-cellulosic constituents, expose cellulose-rich domains, introduce reactive functional groups, and alter the surface energy of the fibers [12,13]. These modifications can also induce fibrillation and change the surface topography, thereby increasing the effective contact area and promoting mechanical interlocking and/or specific chemical interactions with the matrix [12,14]. Physical approaches, including plasma and corona treatments, provide an additional route for modifying surface chemistry and microtopography while limiting changes to the bulk fiber structure [13,15]. Therefore, the selection and severity of the treatment must be controlled according to the fiber composition and matrix chemistry because excessive delignification, oxidation, or surface etching can generate structural defects and adversely affect the intrinsic mechanical performance of the reinforcement.

From a composite design perspective, interfacial compatibility is governed by the coupled effects of surface chemistry and hierarchical morphology rather than by the intrinsic properties of the plant-derived constituent alone. Accordingly, achieving an adequate interface requires controlling the concentration and accessibility of reactive surface groups, surface energy and wettability, surface roughness, fibrillation, and micro- and macroporosity of the constituent phases, which collectively determine matrix wetting, penetration, mechanical interlocking, interfacial adhesion, and stress-transfer efficiency [14,16]. An inappropriate balance between surface polarity and pore architectures may promote moisture uptake, void formation, or interfacial debonding, compromising dimensional stability and long-term durability. Therefore, the engineering of lignocellulosic materials for advanced composite systems should be approached through a structure–

2. Methodology

This critical narrative review was developed based on a structured literature search conducted in the Scopus and Web of Science databases, complemented by consultation of the NASA Technical Reports Server to identify technical documents and institutional publications. No temporal restriction was imposed on the search, as the study aimed to integrate established knowledge on biodiversity and plant-derived materials with recent technological developments related to sustainability and space exploration. The search strategy covered complementary thematic areas relevant to the review, including plant biodiversity, bio-based and natural materials, lignocellulosic fibers, cellulose-based materials, biocomposites, technical and protective textiles, spacesuits and extravehicular mobility units, biomimetic materials, thermal control, regenerative life-support systems, and sustainable strategies for space exploration. The principal keywords included “biodiversity,” “plant diversity,” “sustainable materials,” “bio-based materials,” “natural fibers,” “lignocellulosic fibers,” “cellulose,” “nanocellulose,” “biocomposites,” “biomimetic materials,” “technical textiles,” “protective textiles,” “spacesuits,” “Extravehicular Mobility Unit,” “EMU,” “thermal control,” “life-support systems,” “circularity,” and “in-space manufacturing.”

We selected original research articles, review articles, and NASA reports addressing plant biodiversity, plant-derived materials, natural fiber properties, biomimetics, regenerative life-support systems, thermal control, and spacesuit technologies. The final literature search was conducted on 28 July 2026. No language restrictions were applied during the selection process. Duplicate records retrieved from Scopus and Web of Science were removed using Mendeley Reference Manager v1.69.4 (Elsevier, Amsterdam, The Netherlands). Subsequently, the most complete version of each publication was retained. The keyword co-occurrence network was generated using VOSviewer v1.6.19 (Centre for Science and Technology Studies, Leiden, The Netherlands). The Scopus search for the bibliometric analysis was conducted without temporal restrictions to capture the full evolution of the research field. Keywords were standardized manually, and a minimum occurrence threshold of 2 was established.

3. Results and Discussion

3.1. Requirements and Challenges of Current Spacesuits

Spacesuits designed for extravehicular activities (EVA) are highly complex multilayer textile systems engineered to simultaneously provide environmental protection, pressure containment, thermal regulation, mobility, life support, and protection against micrometeoroids, orbital debris, radiation, and extraterrestrial particles (Figure 2). The spacesuit can be regarded as a miniature spacecraft because it integrates environmental protection, mobility, and life-support functions required to sustain the astronaut during extravehicular activities [19]. The International Space Station Extravehicular Mobility Unit (EMU) operates at a nominal internal pressure of 29.6 kPa (4.3 psia) in a 100% oxygen atmosphere, while the complete system, including the life-support backpack and SAFER, has a mass of approximately 145 kg [20,21]. This pressure, which is substantially lower than the terrestrial atmospheric pressure, generates pressurization forces that increase system stiffness and may restrict joint movement during EVA. Studies on spacesuit mobility have indicated that the combined effects of pressurization and anthropometric fit during EVA can limit the range of motion and increase biomechanical demands [21].

EVA spacesuits and intravehicular activity (IVA) crew garments represent distinct technological systems with different performance requirements. IVA garments are designed for use within the pressurized spacecraft, primarily providing protection during cabin depressurization and other emergencies, whereas EVA suits must protect astronauts during EVA operations in the vacuum of space [22]. Therefore, EVA systems

require multilayer architectures for pressure retention, thermal control, micrometeoroid and environmental protection, and mobility, whereas IVA garments primarily address thermal comfort, moisture management, hygiene, flammability, and long-duration wear [23]. Despite these differences, both systems require pressure and thermal regulation, life-support functions, and sufficient crew mobility [22,23]. Accordingly, the applicability of plant-derived fibers in EVA and IVA systems depends on their functional and environmental requirements.

The National Aeronautics and Space Administration (NASA) crew clothing has historically included a substantial proportion of cotton garments, valued for their comfort during routine activities inside pressurized spacecraft [24,25]. Furthermore, building on the safety requirements established during the Mercury, Gemini, Apollo, and Skylab human spaceflight programs, chemically treated cotton fabrics were used in Space Shuttle flight apparel, ranging from underwear to coveralls and outer jackets, to improve flame resistance [25]. However, for long-duration missions, alternative materials have been investigated to extend garment service life, reduce logistical mass, and enhance fire safety [24]. The materials evaluated include natural fibers, such as merino wool; cotton–rayon blends; and synthetic fibers, such as polyester and modacrylic [24,26]. Ground-based studies and investigations conducted aboard the International Space Station have compared garment wear life, comfort, and astronaut preferences.

The spacesuit's multilayer architecture reflects its functional complexity. EMU configurations may incorporate up to 14 layers in certain regions and approximately 16 layers in flexible sections, with each layer performing a specific function [27]. These components include liquid cooling and ventilation garments, pressure-retention and pressure-containment layers, thermal insulation materials, micrometeoroid protection structures, and an abrasion-resistant outer cover. The documented EMU architecture includes nylon, spandex, urethane-coated nylon, Dacron, neoprene-coated nylon ripstop, aluminized Mylar, Gore-Tex, Kevlar, and Nomex outer fabrics [27,28]. NASA also identifies Kevlar, Nomex, and Gore-Tex as functional components of external textile materials used to provide tear resistance, thermal protection, and water resistance, respectively [28–30]. Therefore, the performance of the spacesuit depends on the interaction among multiple materials rather than on a single structural fiber.

The thermal micrometeoroid garment (TMG)'s multilayer architecture controls heat transfer through textiles and reflective films. Using finite element models, Dziegielewski et al. [31] demonstrated that thermal distribution depends on the architecture and properties of individual layers. Accordingly, plant-derived materials should be evaluated for their thermal conductivity, resistance, emissivity, and dimensional stability.

Durability in a space environment represents another major challenge. During an 18-month exposure experiment in low Earth orbit, samples of textile materials used in spacesuits exhibited solar absorptance increases of 7%–38%, which may alter the thermal balance of the suit surface [32]. Similarly, abrasion tests using lunar dust simulants showed that exposed fibers could undergo an approximately fourfold reduction in tensile strength and elongation, accompanied by an approximately twofold increase in elastic modulus [33]. These changes are particularly relevant to lignocellulosic materials because their structure, chemical composition, and moisture content can significantly influence their mechanical and dimensional stability.

Interaction with extraterrestrial particles is also a critical concern for textile materials. Lunar dust particles exhibit sharp, irregular morphologies, high abrasivity, and electrostatic adhesion, allowing them to accumulate on suit surfaces and contribute to fiber wear, abrasion, and material degradation [34]. Evidence from Apollo spacesuits showed that lunar soil particles could penetrate and remain within outer textile layers, causing fiber separation and fraying. Therefore, NASA has identified abrasion and cut resistance, together with dust protection, as relevant performance requirements for materials intended for future

planetary EVA systems [29]. In addition to particulate abrasion, spacesuit materials must withstand intense radiation and thermal extremes characteristic of planetary surfaces, which can alter optical, mechanical, and thermal properties during extended exposure [32].

Mechanical demands also increase for systems intended for planetary exploration. Although the EMU operates at approximately 29.6 kPa, next-generation suit concepts for planetary exploration, such as the exploration extravehicular mobility unit, have considered operating pressures of up to approximately 56.5 kPa (8.2 psia) [21]. Increased pressure may improve certain physiological and operational aspects; however, it can simultaneously increase the forces required to deform suit joints and, consequently, the demands placed on textile materials and mobility structures [21,31].

In this context, the assessment of plant-derived fibers for space applications should simultaneously consider their mechanical, thermal, and environmental properties. Their incorporation should focus on hybridization strategies and the selective substitution of specific components using natural fibers, cellulose, nanocellulose, or biocomposites without compromising the safety and performance requirements.

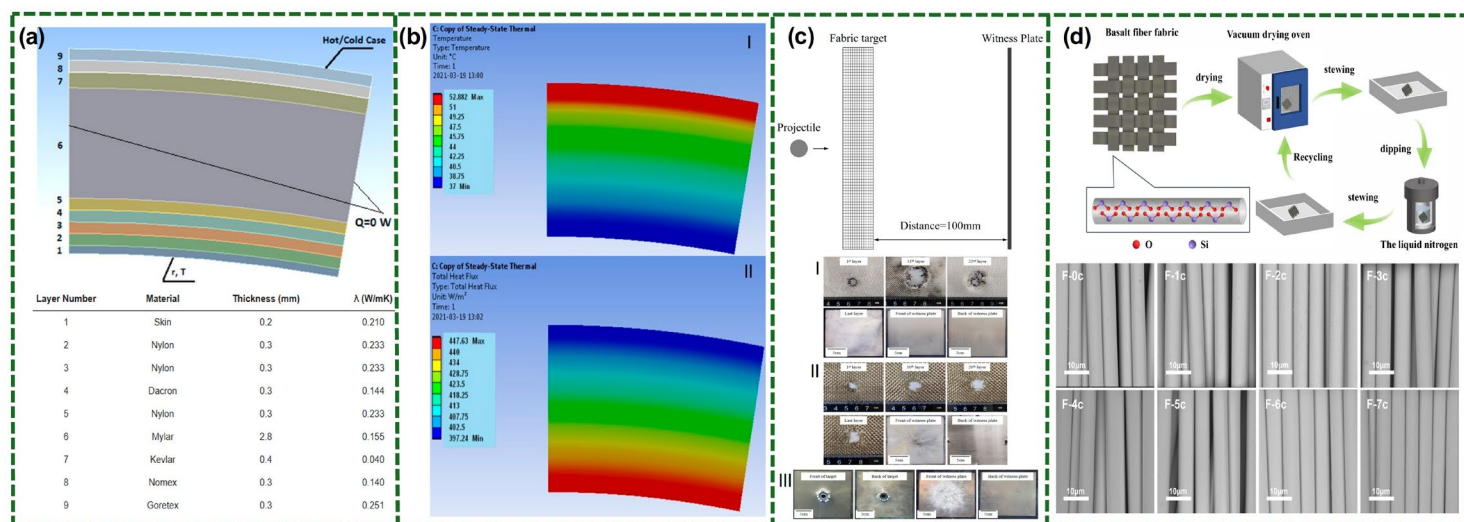


Figure 2. Main requirements and challenges associated with textile materials used in spacesuits for extravehicular activities and planetary exploration. (a) Multilayer architecture designed to integrate pressurization, thermal insulation, and protection [31]; (b) temperature distribution and heat flux under extreme thermal conditions [31]; (c) assessment of fabric resistance to high-velocity impacts associated with micrometeoroids and orbital debris [35]; and (d) morphological evaluation of basalt-fiber fabrics subjected to thermal cycling and ultraviolet radiation, as an approximation of durability challenges in lunar applications [36]. Images adapted and combined from the original sources and used under a Creative Commons Attribution (CC BY 4.0) license.

3.2. Potential of Plant Biodiversity for Space Sustainability

The literature indicates that plant biodiversity can contribute to the sustainability of space technologies through resource recycling, bio-based material production, and adaptation to extreme environments. Plants can absorb CO₂, produce O₂, contribute to water recycling, and process waste, making them relevant to closed-loop life-support systems [37,38]. Studies on bioengineered plants adapted to microgravity and high-CO₂ atmospheres highlight the potential of plant-based systems under spaceflight conditions [39]. Renewable plant-derived materials, including wood-based materials, are also being investigated as alternatives for space technologies, with the potential to reduce conventional resource use and waste generation [40]. However, these findings do not yet demonstrate the direct use of such materials in the manufacturing of spacesuits.

Consequently, their current contribution lies primarily in informing sustainable material strategies rather than enabling the immediate replacement of conventional systems.

The sustainability of bio-based materials should be assessed within a circular resource-utilization framework. Plant-derived materials could be integrated into closed-loop systems in which biomass is produced, processed into functional materials, repaired, reused, and ultimately recycled. In this context, their sustainability benefits could extend beyond replacing conventional Earth-sourced fibers to reducing dependence on Earth resupply through local or partially local material production and resource recovery. Future research should focus on in-space manufacturing, reparability, modularity, and end-of-life recovery to support more sustainable spacesuit design.

3.3. Bioinspired Principles for Sustainable Spacesuits

Based on the analyzed studies, the following four principles show potential for transfer to sustainable spacesuit development: resource-use efficiency, multifunctionality, adaptation to extreme conditions, and material circularity (Table 1). Plant-based systems provide conceptual references for efficient resource use and closed-loop processes [37,38]. Studies of plants exposed to extraterrestrial environments have also shown that variations in gravity, water availability, and atmospheric composition induce morphophysiological responses that may inform the development of responsive materials [39]. In parallel, plant-derived fibers and materials can partially replace fossil-based feedstocks in textile applications when combined with appropriate processing and material-recovery strategies [40].

The transfer of biomimetic principles to spacesuits should focus primarily on structural and functional strategies rather than the simple substitution of synthetic fibers with plant-derived materials. Hierarchical biological structures can simultaneously regulate heat transfer, moisture transport, and surface interactions. A biomimetic textile inspired by the fibrous structure of skin exhibited a thermal conductivity of $0.07 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, mechanical strength of up to 10 MPa, and elongation at break exceeding 300%, demonstrating the potential of multiscale organization to combine deformability and thermal insulation [41]. Similarly, a bioinspired metafabric achieved a solar reflectance of 97.3%, an infrared emissivity of 91.3%, and a temperature reduction of 7.3°C while maintaining a hydrostatic pressure resistance of 67.4 kPa and high water-vapor transmission [42]. These examples illustrate how biological principles can inform multifunctional textile architectures rather than single-property material substitution.

Material circularity is also relevant as the mission duration and distance from Earth increase. Accordingly, spacesuit materials could be designed as modular, replaceable, repairable, and recoverable components, reducing the need to replace entire garments. Plant-derived polymers, cellulose-based materials, and bio-based composites could contribute to this approach if compatible feedstocks and processing routes become available. The integration of additive manufacturing, fiber processing, reversible joining, and material recovery could support partial in-space production and maintenance. However, the production of qualified spacesuit materials from biological feedstocks in extraterrestrial environments has not yet been demonstrated. The Lunar Palace 365 system, which integrates plants, microorganisms, and physicochemical processes, achieved more than 98% material closure, demonstrating the feasibility of highly circular architectures for isolated environments [43].

Overall, these principles could inform the development of multifunctional components, hierarchical structures, recoverable materials, and passive responsive systems for spacesuits. However, direct implementation in operational spacesuits remains undeveloped, highlighting a technological gap between bioinspired mechanisms and

textile architectures capable of simultaneously satisfying thermal, mechanical, moisture-management, environmental-protection, and circularity requirements.

Table 1. Bioinspired principles derived from plant biodiversity and their potential for sustainable spacesuit application.

Plant-Based Principle	Potential Applications in Spacesuits	Expected Contribution	Ref.
Resource-use efficiency	Structures requiring lower materials and energy consumption	Mass reduction and requirements for consumables	[37,41]
Multifunctionality	Thermal/mechanical protection and moisture management	Reduced number of components	[39,42]
Adaptation to extreme weather conditions	Reliable materials and surfaces to environmental stimuli	Enhanced functional stability	[39]
Material circularity	Recoverable materials and integration of waste streams	Reduced material losses and waste generation	[38,42]
Renewable-origin materials	Bio-based fiber polymers, and composites	Reduced dependence on fossil fuel resources	[40]

Note: Information compiled and synthesized by the authors based on the cited references.

3.4. Comparison of Plant Fiber Performance with High-Performance Space Materials

A comparison of mechanical properties indicates that some plant fibers exhibit promising mechanical performance for bio-based materials (Table 2). The softness, strength, and fiber purity of Peruvian Pima cotton demonstrate the potential of plant-derived feedstocks for high-value textile applications [44]. Among fibers with greater structural potential, flax exhibits a tensile strength of 345–1830 MPa, whereas hemp reaches 550–1110 MPa and ramie 400–938 MPa, with densities close to 1.5 g/cm³. Kevlar 49, which is used in spacesuit components, exhibits a tensile strength of approximately 3650 MPa and a Young’s modulus of 124 GPa [45,46]. Because these values were compiled from different sources and may have been obtained under different testing conditions, the comparison should be interpreted as indicative rather than a direct performance equivalence. Even the maximum reported tensile strength of flax corresponds to approximately 50% of that of Kevlar 49, indicating a substantial difference in tensile strength when the fibers are considered individually. However, the strength-to-weight ratio provides a different perspective: flax can reach approximately 1220 MPa·cm³/g, whereas hemp can reach 740 MPa·cm³/g [45].

Other plant-derived fibers also show notable specific strength values: bamboo fiber reaches up to 1333 MPa·cm³/g, while banana fiber reaches up to 1306 MPa·cm³/g, both approaching or exceeding the upper range reported for flax [47]. Furthermore, bamboo exhibits a comparatively low density of 0.6–1.1 g/cm³, illustrating the potential mass advantage of some plant-derived reinforcements. In contrast, materials such as bagasse combine very low density (0.55–1.25 g/cm³) with substantially lower tensile strength, highlighting the considerable variation among plant-derived feedstocks [47]. Plant fibers can be considered for several material strategies, including their use as standalone textile reinforcements, reinforcement phases in hybrid materials, and secondary or multifunctional structures [7,8]. Hybridization with synthetic or other high-performance fibers can combine complementary properties and mitigate some limitations of natural fibers, although its effectiveness depends on fiber type, fiber ratio, interfacial adhesion, and processing conditions [47,48].

However, tensile strength measured at the individual-fiber level should be considered only as a preliminary indicator of structural potential and cannot be directly extrapolated to a spacesuit textile. At the fabric and component levels, tear, cut, abrasion, and puncture resistance are critical because the performance depends not only on the intrinsic fiber properties but also on yarn construction, fabric architecture, inter-fiber interactions, and multilayer configuration. The reported tensile strengths of plant fibers provide a basis for preliminary material screening; their suitability for spacesuit applications, however,

requires textile- and component-level validation under representative environmental conditions.

These comparisons indicate that plant fibers are not currently suitable as direct substitutes for high-performance fibers in primary load-bearing or pressure-retaining spacesuit components. Their application is relevant to hybrid structures, secondary components, repairable modules, and multifunctional bio-based systems. Their sustainability potential should be assessed within a circular mission architecture that considers resource recovery and reuse alongside mechanical performance.

Table 2. Mechanical properties of plant fibers and a high-performance fiber used in space applications.

Fiber	Density (g/cm ³)	Tensile Strength (MPa)	Young's Modulus (GPa)	Specific Strength (MPa·cm ³ /g)	Ref.
Flax	1.5	345–1830	27–80	230–1220	[45]
Hemp	1.5	550–1110	58–70	370–740	
Ramie	1.5	400–938	44–128	270–620	
Jute	1.3–1.5	393–800	10–55	300–610	
Sisal	1.3–1.5	507–855	9.4–28	362–610	
Bamboo	0.6–1.1	140–800	11–35.9	127–1333	[47]
Banana	0.7–1.35	54–914	7.7–32	40–1306	
Pineapple	0.8–1.6	148.4	10.5	93–186	
Kenaf	1.1–1.2	150–250	10–20	125–227	
Coir	1.2–1.5	95–593	2.8–6	63–494	
Abaca	1.5	400–980	6.2–72	267–653	[46]
Bagasse	0.55–1.25	20–350	0.5–27.1	16–636	
Kevlar 49	≈1.44	≈3650	≈124	≈2535	

Note: Information compiled and synthesized by the authors based on the cited references.

3.5. Plants and Plant-Derived Materials with Potential for Space Applications

Analysis of the selected studies identified several plant species and plant-derived materials with potential relevance as biomass sources, bioengineering models, or renewable materials (Table 3). Lemnaceae species are notable for their rapid growth, oxygen production, and CO₂ sequestration, supporting their use in regenerative systems and potential biomass production for bio-based materials [37]. In hydroponic systems, barley has been investigated to evaluate stress responses and nanofertilization, providing insights into plant adaptation under controlled environmental conditions [49]. Wood-derived materials have also been considered for space applications, while bioengineered plants may integrate food, oxygen, and biomass production within low-waste systems [40,50]. Although these species and materials are not directly associated with spacesuit manufacturing, their biomass productivity, stress adaptation, bioengineering potential, and renewable-material characteristics may inform future strategies for sustainable space-material production. These examples should therefore be considered indirect contributors to space-material development, primarily through biomass production, resource regeneration, and bioengineering strategies, rather than as direct candidates for spacesuit fabrication.

Plant-derived fibers and cellulosic materials provide a more direct pathway for translating plant biomass into functional materials. Natural fibers and lignocellulosic residues are increasingly being investigated for sustainable textile applications owing to their renewable origin, functional properties, and potential for recycling and waste valorization [51]. Recent assessments of cellulosic textile fibers have also included unconventional sources such as cornhusk, pineapple leaf, banana leaf, sugarcane bagasse, and other plant-derived feedstocks, demonstrating the expanding material base for bio-based textile production [52]. However, their suitability for spacesuit applications remains

to be established because thermal protection, mechanical durability, moisture management, radiation resistance, and environmental stability are substantially more demanding than those of conventional textile applications.

Table 3. Plant species and plant-derived materials with potential relevance to sustainable production of space-based materials.

Plant Species/Material	Relevant Characteristic	Potential Contribution to Space-Material Development	Ref.
Lemnaceae	Rapid growth, O ₂ production, and CO ₂ sequestration	Biomass production within regenerative systems	[37]
Barley	Stress adaptation under hydroponic conditions	Model for bioengineering stress-resilient plants	[49]
Wood-derived materials	Renewable origin and bio-based potential	Renewable materials for space applications	[40]
Bioengineered plants	Multifunctionality and resource-use efficiency	Production of biomass and multifunctional material	[50]
Natural plant fibers and lignocellulosic residues	Renewability, functional properties, and potential for waste valorization	Bio-based textile materials and reinforcement components	[51,52]

Note: Information compiled and synthesized by the authors based on the cited references.

3.6. Nanocellulose and Advanced Cellulosic Materials

One of the most promising routes for converting plant biomass into high-performance functional materials is nanocellulose, particularly in the form of cellulose nanofibrils (CNF), cellulose nanocrystals (CNC), and nanocellulose aerogels [53]. CNFs typically have diameters of approximately 2–20 nm and lengths exceeding 1 µm, whereas CNCs generally have diameters of the order of 5–20 nm and lengths of 100–200 nm [54]. Their high aspect ratio, hydroxyl-functionalized surfaces, and ability to form three-dimensional networks enable the control of porosity, stiffness, and thermal transport. Nanocellulose aerogels generally exhibit a porosity of >90%, low density, and tunable porous architectures [55]. In hierarchical nanocellulose/silica composites, thermal conductivities of $\leq 20 \text{ mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ have been reported, demonstrating their potential for highly efficient thermal insulation applications [53]. However, their high hydrophilicity remains a critical limitation: water absorption increases thermal conduction and reduces dimensional stability, while the inherently cellulosic nature of unmodified aerogels also results in high flammability [54,55].

However, the low thermal conductivity reported for nanocellulose aerogels does not directly demonstrate superior insulation performance for spacesuits. Thermal TMG employs aluminized mylar multilayer insulation, which primarily suppresses radiative heat transfer under vacuum. Thus, the bulk thermal conductivity of aerogels is not directly comparable with the effective thermal performance of mylar multilayer insulation because their dominant heat-transfer mechanisms differ. Nanocellulose aerogels may be promising candidates for complementary insulation layers, but their performance must be validated under representative vacuum and thermal conditions.

The interest in nanocellulose for space applications lies in its incorporation into aerogels, membranes, coatings, foams, and multifunctional biocomposites. Chemical modification, crosslinking, and inorganic phase incorporation can enhance mechanical strength, hydrophobicity, thermal stability, and radiation protection. Recent studies have demonstrated that functionalized oxidized nanocellulose films can combine high mechanical strength with tunable UV protection [53,56], while recent reviews indicate that aerogel functionalization can impart hydrophobic, electrically conductive, antimicrobial, and electromagnetic shielding properties [57]. In spacesuits, these characteristics could be exploited in secondary layers for thermal insulation, thermal regulation, environmental barrier functions, or textile-based sensors, while maintaining high-performance synthetic fibers in regions subjected to the highest mechanical loads. The main limitation remains

the need to demonstrate stability following simultaneous exposure to vacuum, radiation, thermal cycling, abrasion, and low humidity—conditions that are still insufficiently represented in conventional nanocellulose studies.

3.7. Engineering and Functionalization of Plant Fibers

The functionalization of plant fibers is a strategy for mitigating limitations such as hydrophilicity, low dimensional stability, and limited fiber–matrix adhesion prior to their use in engineering biocomposites (Table 4). Alkaline treatments, silanization, acetylation, maleinization, and surface coatings can partially remove non-cellulosic constituents, modify surface morphology, and improve interfacial stress transfer [45,58]. However, the magnitude of these improvements varies considerably according to the treatment conditions, fiber type, and polymer matrix. For example, in flax/PP composites, treatment with 5% NaOH for 120 min increased tensile strength, tensile modulus, flexural strength, and flexural modulus by approximately 22.8%, 47.3%, 146%, and 113%, respectively, compared with the untreated system [8]. The improvement was not uniform across mechanical properties, with the largest gains occurring in flexural performance. In flax fiber-reinforced PLA composites, combined surface treatments produced tensile strengths of up to 102.5 ± 5.2 MPa, a Young's modulus of 25 ± 1.4 GPa, and a flexural strength of 140 ± 6.9 MPa [59,60]. In another comparative system, fiber modification increased tensile strength by approximately 80%, Young's modulus by 300%, and flexural strength by 27% relative to the unreinforced matrix [59]. Because these studies involve different fiber treatments, matrices, and testing configurations, the reported values should be interpreted as system-specific improvements rather than as directly interchangeable performance gains.

The functionalization benefits must be considered together with its potential disadvantages. Alkaline treatment can improve fiber–matrix adhesion by removing surface impurities and part of the hemicellulose and lignin fractions; however, excessive treatment can damage the cellulose structure and reduce fiber strength [8,61]. Consequently, increasing treatment severity does not necessarily result in a gain in performance. Chemical consumption, washing requirements, additional processing steps, and possible loss of fiber integrity should therefore be considered when evaluating the overall suitability of a modification strategy. For space applications, functionalization should be optimized according to requirements such as moisture resistance, thermal stability, abrasion resistance, dimensional stability, radiation tolerance, and compatibility with low-outgassing matrices. The available evidence therefore supports a selective rather than universal approach to functionalization, in which the measured improvement in a target property is evaluated against the associated processing requirements and potential degradation of other properties.

The functionalization of cellulosic materials can extend the performance of plant-derived fibers and substrates beyond their intrinsic mechanical properties, enabling the incorporation of specific functions of interest for space textile materials.

For example, cotton fabric functionalized with a WS_2/CoS_2 metal–organic framework structure and subsequently carbonized exhibited strong electromagnetic-wave absorption with potential for electromagnetic interference (EMI) shielding, achieving a minimum reflection loss of -51.26 dB at 17.36 GHz at a thickness of 2 mm, with absorption-dominated performance associated with multiple reflections and impedance matching within the multicomponent architecture [62].

Cotton modified with carbon black and polydimethylsiloxane achieved an EMI shielding effectiveness of 42.9 dB while simultaneously exhibiting superhydrophobicity [63]. Similarly, cellulose-derived carbon aerogel/rGO–PDMS composites achieved an EMI shielding effectiveness of 51 dB with only 3.05 wt% filler loading, approximately 3.9 times

higher than that of a conventionally blended composite with the same filler content, due to the formation of a three-dimensional conductive network [64]. In another lignocellulosic fiber, mild alkaline treatment of jute with NaOH increased tensile strength by approximately 82% and elongation at break by 45%, while hydrophilicity decreased by 50.5%, demonstrating that the same modification strategy can simultaneously improve mechanical properties and moisture-related surface behavior [65].

These results show that the modification of cellulosic substrates can produce measurable performance improvements and introduce functionalities that are not present in the unmodified material. However, the magnitude of the improvement depends on the fiber, treatment concentration and duration, as well as the matrix and material configuration. Moreover, more severe alkaline treatments can cause cellulose structure degradation and fiber strength; therefore, a higher degree of functionalization does not necessarily result in better performance [8,61,65]. In the context of space textiles, the functionalization of cellulosic fibers should therefore be directed toward a specific property or function and evaluated by comparing the magnitude of the performance improvement with the potential penalties introduced by the treatment.

These results suggest that plant-derived fibers and cellulose-based materials should not be evaluated solely according to their mechanical properties. The relevant criterion is the balance between the magnitude of the property improvement, the preservation of other critical properties, and the complexity introduced by the modification process. Selective surface engineering, coatings, and hybrid architectures may therefore be more appropriate for non-critical or multifunctional components, where specific properties, such as hydrophobicity, electromagnetic shielding, thermal insulation, or interfacial compatibility, can be targeted without requiring plant-derived fibers to directly replace established high-performance fibers, such as Kevlar or Nomex, in pressure-retaining and primary protective regions (Figure 3).

Table 4. Integrated assessment of plant-derived fibers and bio-based materials for sustainable spacesuit applications.

Material	Key Property	Main Limitation	Modification/Engineering Strategy	Potential Function of the Spacesuit
Flax	High specific strength	Moisture sensitivity	Alkaline treatment, silanization	Hybrid reinforcement
Hemp	High tensile strength	Property variability	Surface treatment, hybridization	Structural reinforcement
Ramie	High tensile strength and modulus	Moisture uptake	Coating, chemical functionalization	Reinforcement layers
Jute	Low density, renewable origin	Lower mechanical performance	Surface modification, hybrid biocomposites	Secondary structures
Sisal	Good specific strength	Moisture sensitivity and variability	Alkaline treatment, hybridization	Reinforcement
Nanocellulose	Low density, high aspect ratio	Hydrophilicity	Crosslinking, surface functionalization	Thermal/functional layers
CNF	High aspect ratio, network-forming capability	Moisture sensitivity	Chemical functionalization	Membranes/coatings
CNC	High stiffness	Brittleness	Polymer hybridization	Nanocomposites
Cellulose aerogel	>90% porosity and very low thermal conductivity	Flammability/moisture sensitivity	Inorganic phase incorporation and crosslinking	Thermal insulation

Note: Original table developed by the authors.

This application-oriented comparison connects the material-level properties summarized in Tables 2 and 4 with specific spacesuit functions and qualification

requirements, highlighting where bio-based materials currently provide measurable performance and where application-level validation remains necessary (Table 5).

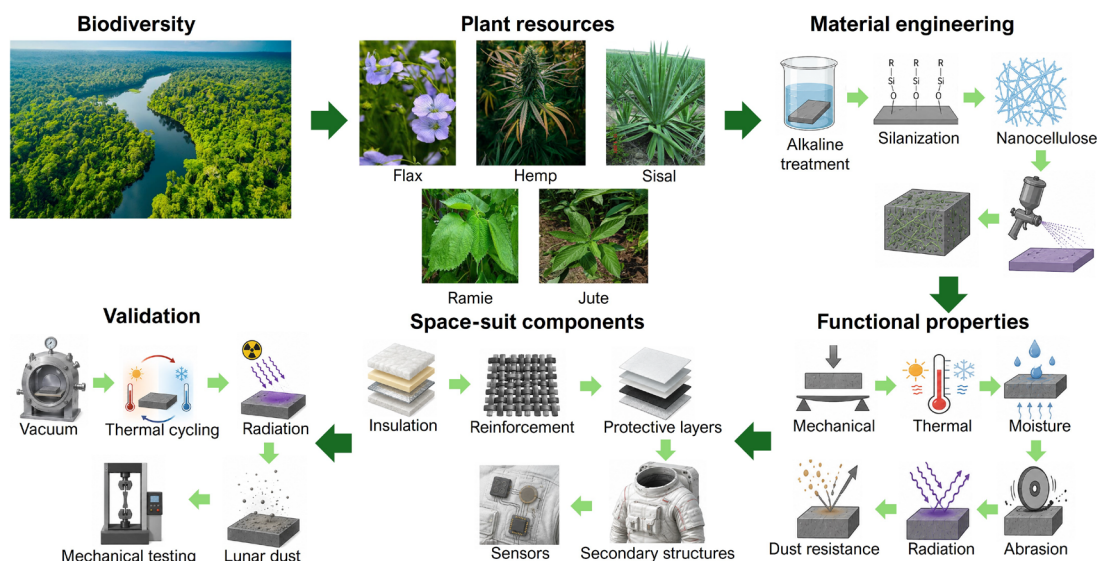


Figure 3. Integration of plant-derived fibers into sustainable spacesuits. Original figure developed by the authors.

Table 5. Application-oriented comparison of spacesuit components, requirements, current materials, and best reported bio-based performance.

Component	Function	Requirement/Test Standard	Current Performance	Best Bio-Based Performance
Outer protective layer	Protection against abrasion, tearing, cutting, and puncture	Abrasion, tear, cut, and puncture resistance	High-performance protective textile systems incorporating Kevlar and Nomex. No directly comparable quantitative data available for abrasion, tear, cut, and puncture resistance	No data
Thermal insulation	Reduction in heat transfer	Thermal insulation and thermal cycling under vacuum conditions	Aluminized Mylar multilayer insulation in thermal micrometeoroid garments. No directly comparable quantitative value available	Nanocellulose/silica aerogels: thermal conductivity $\leq 20 \text{ mW m}^{-1} \text{ K}^{-1}$. Validation under representative spacesuit conditions remains necessary
Barrier layer	Protection against moisture and environmental exposure	Moisture uptake, dimensional stability, and outgassing (ASTM E595 [66])	Gore-Tex and coated textile systems. No directly comparable quantitative value available	No data
Structural reinforcement	Mechanical load transfer and reinforcement	Tensile strength, modulus, fatigue, and dimensional stability	Kevlar 49 fiber: tensile strength $\approx 3650 \text{ MPa}$; Young's modulus $\approx 124 \text{ GPa}$; density $\approx 1.44 \text{ g cm}^{-3}$. These values refer to individual fibers, not the complete structural component	No data
Regolith-exposed surface	Resistance to lunar-dust abrasion and particle interaction	Abrasion, cut, and penetration resistance under regolith exposure	Existing spacesuit textile systems. No directly comparable quantitative value available	No data

Note: Original table developed by the authors.

Hybrid and Multilayer Architectures for Spacesuit Applications

The multilayer architecture of spacesuits provides distinct functional locations for the selective incorporation of plant-derived materials. Although detailed descriptions may comprise up to 16 material layers, thermal models can group physically distinct sublayers into functionally equivalent layers; for example, an eight-layer representation

has been used for the TMG, with multiple aluminized Mylar plies treated as a single equivalent layer [31]. Within this architecture, plant-derived materials could be considered primarily for secondary reinforcement layers using flax, hemp, or ramie; thermal-insulation layers using porous nanocellulose or cellulose aerogels; and intermediate multifunctional layers using functionalized cellulose-based structures. CNF aerogel fibers have demonstrated low thermal conductivity and coaxial core-sheath architectures suitable for lightweight fibrous insulation [67], while cellulose nanohybrid aerogel fibers have provided combined thermal management and electromagnetic shielding functions in textile structures [68].

These potential integrations should remain function-specific rather than being considered replacements for the complete spacesuit textile system. Plant-derived materials could therefore contribute to insulation, secondary reinforcement, or multifunctional intermediate layers, whereas the pressure-retaining layer and primary external protection against abrasion, cutting, puncture, and micrometeoroid/debris impact would remain dependent on validated high-performance materials. Recent cellulose-based coaxial fibers demonstrate promising flexibility, hydrophobicity, and textile processability [69]; however, these material-level results do not establish performance under vacuum, thermal cycling, radiation, abrasion, or regolith exposure. Consequently, a selective hybrid architecture represents a realistic near-term strategy in which plant-derived components provide specific functions within a multilayer system while qualified materials retain critical protective functions.

3.8. Structure–Property–Function Relationships of Plant Fibers for Space Applications

The properties of plant fibers are governed by a hierarchical architecture extending from their chemical composition to the organization of cellulose microfibrils [70]. The secondary cell wall consists primarily of crystalline cellulose embedded within a matrix of hemicelluloses and lignin, and one of the microfibrils relative to the longitudinal axis is one of the main factors governing the mechanical response [70–72]. Approximate microfibrillar angles of 10°, 6.2–11°, 8°, and 20° have been reported for flax, hemp, jute, and sisal fibers, respectively; lower microfibrillar angles favor load transfer along the longitudinal direction and, consequently, higher stiffness and specific strength [73]. In flax fibers, the secondary cell wall has an approximate thickness of 5–15 µm and a high cellulose content, whereas variations in diameter, the presence of defects, and ultrastructural organization account for part of the observed scatter in mechanical properties [74,75].

This variability is not limited to anatomical features but can also arise from species, cultivar, growing conditions, maturity, geographical origin, extraction method, and subsequent processing or surface treatment. Consequently, the nominal mechanical and thermal values reported for a given plant fiber should be interpreted as material-specific ranges rather than fixed properties. This variability is particularly relevant for space-related applications because it requires reproducibility, dimensional stability, and predictable performance under thermal, vacuum, radiation, and mechanical loading conditions.

Micromechanical studies of hemp fibers have further demonstrated that the apparent modulus dependence on fiber diameter is primarily associated with cellulose crystallinity and microfibrillar angle [76]. Chemical composition also plays a structural role: flax fibers contain approximately 64.1% cellulose, 12.0% hemicellulose, and 2.0% lignin, whereas hemp fibers contain approximately 68.1%, 15.1%, and 10.6% cellulose, hemicellulose, and lignin, respectively [77]. Furthermore, increases in cellulose crystallinity and crystallite size have been associated with a shift in thermal decomposition toward higher temperatures in different lignocellulosic fibers [78]. Fiber selection for space applications should not be based solely on nominal strength but on the combined effects of microfibrillar orientation, crystallinity, chemical composition, diameter, defects, cell-wall architecture, species, growing conditions, maturity, geographical origin, extraction

method, and subsequent treatment. Such variability must be considered when assessing the reproducibility and reliability of plant-derived materials for space applications.

This structure–property relationship enables a more precise correspondence between fiber architecture and its potential function within a textile system (Figure 4). Structures with highly oriented microfibrils may favor reinforcement elements subjected predominantly to longitudinal loads, whereas architectures characterized by high porosity or a large lumen may be more relevant to insulation and mass-reduction strategies [71]. For example, highly porous cellular fiber structures can exhibit a substantial hollow fraction, as observed in poplar fibers, where the lumen accounted for approximately 80% of the cellular structure and the mean fiber diameter was 5.2 μm [79]. At a lower structural scale, reducing the dimensions of cellulosic building blocks can radically modify the structure–function relationship: oriented cellulosic materials have achieved strengths on the order of 1 GPa and moduli of up to 75 GPa when fiber orientation approaches a unidirectional configuration [80]. These findings indicate that space-related functions should be assigned according to the multiscale architecture of the material: fibers with high orientation and structural continuity for reinforcement, high-aspect-ratio cellulosic networks for membranes and functional layers, and porous structures for thermal insulation and mass reduction. However, this functional translation should be regarded as a design hypothesis because the structure–property relationships demonstrated under terrestrial conditions have not yet been validated under vacuum, radiation, thermal cycling, and extraterrestrial regolith exposure.

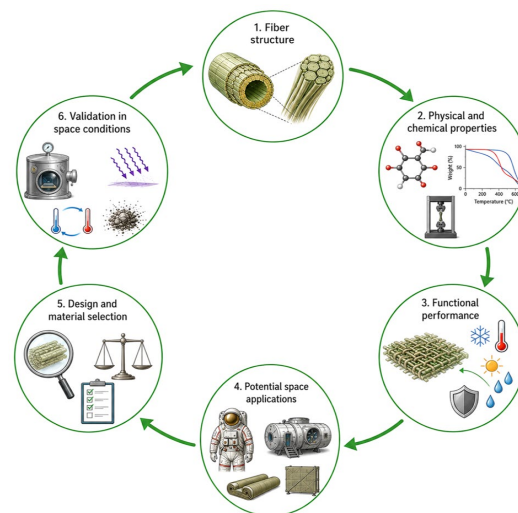


Figure 4. Structure–property–function cycle for space applications. Original figure developed by the authors.

3.9. Molecular Interactions, Interfaces, and Structure–Processing–Property Relationships in Hybrid Materials

3.9.1. Molecular Composition and Interactions in Lignocellulosic Fibers

The performance of plant-derived hybrid materials depends not only on the intrinsic properties of each component but also on the interactions developed at the fiber–matrix, nanocellulose–polymer, and coating–substrate interfaces. Cellulose constitutes the main structural phase in lignocellulosic fibers and consists of repeating β -D-glucopyranose units linked through β -(1 $\rightarrow$ 4) glycosidic bonds, with its empirical formula represented as $(\text{C}_6\text{H}_{10}\text{O}_5)_n$ [81]. The numerous hydroxyl ($-\text{OH}$) groups in cellulose promote the formation of intra- and intermolecular hydrogen bonds, whereas hydroxyl, carbonyl, ether, and methoxy groups in hemicellulose and lignin modify the polarity and surface reactivity of the fiber [82,83]. This composition simultaneously accounts for the high cohesion of cellulose microfibrils and the characteristic hydrophilicity of plant fibers.

Hemicelluloses are heterogeneous, branched polysaccharides composed mainly of xylans, mannans, xyloglucans, and other substituted polysaccharides, whose amorphous structure enables interactions with cellulose microfibrils and other cell wall components. Their association with cellulose is mediated mainly by hydrogen bonding and contributes to the organization of the polysaccharide matrix, whereas their chemical heterogeneity influences the fiber surface's accessibility and reactivity [84]. Lignin, in contrast, is a three-dimensional aromatic polymer derived from phenylpropanoid units and contains phenolic and aliphatic hydroxyl, methoxy, and ether groups. These functionalities promote noncovalent interactions with cellulose and hemicelluloses, while covalent lignin–carbohydrate linkages can further stabilize the secondary cell wall network and contribute to its mechanical integrity and chemical deconstruction resistance [85].

Pectin is another structurally relevant polysaccharide, particularly in primary cell walls and middle lamellae, and is characterized by galacturonic-acid-rich domains, such as homogalacturonan and rhamnogalacturonan, with neutral-sugar substitutions depending on its molecular structure. Its carboxyl-containing groups contribute to hydration and ionic interactions, while its association with other wall polymers is influenced by its degree of esterification and molecular organization [86]. Experimental solid-state nuclear magnetic resonance and extraction studies have demonstrated direct spatial proximity and interactions between pectin and cellulose, indicating that pectin can participate in the cohesive organization of the polysaccharide network rather than acting solely as an external matrix component [87]. The relative composition and molecular accessibility of hemicellulose, lignin, and pectin contribute to the polarity, hydration, interfacial reactivity, and adhesion behavior of lignocellulosic fibers, thereby influencing their compatibility with polymer matrices and the resulting structure–processing–property relationships.

3.9.2. Hydrogen Bonding and Interfacial Adhesion

At the molecular scale, the characteristic interaction between cellulose chains can be represented as Cell–OH...O–Cell, in which the –OH group acts as a hydrogen-bond donor and the oxygen atom of another hydroxyl or ether group acts as a hydrogen-bond acceptor [88]. These interactions contribute to the organization of cellulose microfibrils and, together with crystallinity and molecular orientation, determine a substantial fraction of the stiffness and strength of the fiber [89]. Atomistic studies have demonstrated that hydrogen bonds significantly contribute to the strength of cellulose interfaces, with individual bond forces on the order of 10^{-10} N, indicating that modifications to surface chemistry can directly affect macroscopic mechanical behavior [90,91]. However, when a plant fiber is incorporated into a hydrophobic matrix, such as polypropylene or certain thermoset matrices, a chemical mismatch arises between the –OH-rich surface and the low-polarity matrix [92]. This results in limited interfacial adhesion, void formation, and reduced stress transfer, representing one of the main constraints in lignocellulosic biocomposites [82,83].

3.9.3. Effect of Processing on the Fiber–Matrix Interface

Processing enables the fiber–matrix interface to be modified through alkaline and oxidative treatments, silanization, acetylation, plasma treatment, or the incorporation of compatibilizing agents. These treatments partially remove hemicellulose, lignin, waxes, and extractives, increase surface roughness, and enhance the availability of functional groups that can interact with the matrix [14]. However, excessive treatment intensity can induce fibrillation, reduce fiber length, or degrade cellulose, resulting in a decrease in mechanical properties [93]. Consequently, processing severity and surface modification influence interfacial quality and, ultimately, the performance of the final material. From a structural perspective, a homogeneous interface with strong adhesion promotes efficient load transfer from the matrix to the reinforcing phase, whereas a weak interface promotes stress

concentration and failure mechanisms such as interfacial debonding, fiber pull-out, and crack propagation [14,92].

3.9.4. Nanocellulose, Dispersion, and Reinforcement Efficiency

The incorporation of nanocellulose can substantially increase the interfacial area because of its high aspect ratio and nanoscale dimensions [81]. Depending on the source and isolation process, cellulose nanocrystals can exhibit diameters on the order of 5–50 nm and lengths of approximately 100–500 nm, whereas cellulose nanofibrils can reach micrometer-scale lengths [94]. This architecture provides many surface groups that can form hydrogen bonds and interact with hydrophilic polymers [95]. However, the same hydrophilic character can promote aggregation when nanoparticles are incorporated into hydrophobic matrices, making dispersion one of the critical processing parameters [14]. Consequently, increasing the nanocellulose content does not necessarily result in a continuous improvement in properties: above an optimum loading, agglomeration may occur and reduce reinforcement efficiency [96].

3.9.5. Cellulose–Montmorillonite Architecture and Hybrid Materials

Combining cellulose with a mineral phase, such as montmorillonite, is a particularly relevant strategy for hybrid materials. Clay platelets have a layered structure and high specific surface area, enabling interactions with polymer chains and cellulosic fibers [97]. Simultaneous improvements in mechanical strength, thermal stability, and barrier properties have been observed in cellulose/montmorillonite nanocomposites when the clay is adequately dispersed [98]. In hybrid systems based on carboxymethyl cellulose, guar gum, and montmorillonite, the tensile strength of 53.5 ± 1.10 MPa, elongation at break of $83.5 \pm 4.35\%$, toughness of 32.16 ± 1.04 MJ/m³, and a temperature corresponding to 50% degradation of approximately 304 °C have been reported [99]. These results demonstrate that interfacial architecture modification can simultaneously enhance mechanical and thermal properties, which are relevant characteristics for materials required to operate under demanding environmental conditions.

3.9.6. Interactions Between Polysaccharides and Bioactive Components

The interactions between polysaccharide matrices and bioactive components should also be considered. For example, cellulose and chitosan can form networks stabilized by hydrogen bonding and electrostatic interactions [100]. Modifying the ratio between the two phases enables the control of swelling behavior, porosity, mechanical strength, and antimicrobial activity. Bacterial cellulose/chitosan hydrogels have been developed that achieved bacterial reductions of approximately 88%, demonstrating that the composition and organization of the polymeric network can simultaneously influence structural and functional properties [101]. In nanocellulose/chitosan hydrogels, increases of approximately 64.9% in tensile strength and 83.6% in swelling capacity have also been reported, accompanied by a significant reduction in pore size, highlighting the influence of nanostructure on mechanical and transport properties [102].

3.9.7. Multiscale Structure–Processing Relationship Analysis

These interactions can be organized into four levels from a multiscale perspective. At the molecular scale, functional groups govern hydrogen bonding, electrostatic interactions, and intermolecular forces. At the nanoscale, crystallinity, orientation, and nanoparticle dispersion influence material behavior. At the microscale, porosity, phase distribution, surface roughness, and defects govern crack propagation and moisture transport. Finally, at the macroscale, these characteristics are manifested as tensile strength, elastic modulus, elongation, thermal stability, water absorption, permeability, and durability.

Accordingly, structure, processing, and properties should not be analyzed independently but rather as coupled variables within a unified materials design framework [103].

3.9.8. Application of Multiscale Architecture to Spacesuits

This perspective is particularly relevant to spacesuit materials. Models available through the NASA Open Data Portal for different generations of spacesuits, including Gemini, Mark III, and EMU, illustrate the multilayered and structurally differentiated architecture of these systems, in which distinct components contribute to protection, mobility, and environmental control [104–106]. Although these datasets do not provide the molecular composition of each layer directly, they constitute useful structural references for understanding the need to design hybrid materials with differentiated and mutually compatible properties across multiple scales.

3.9.9. Micro-CT, Aging, and Material Validation for Space Environments

In addition, X-ray micro-computed tomography (micro-CT) datasets available from NASA enable the three-dimensional characterization of phase distribution, porosity, defects, and internal architecture in materials and composite systems [107]. This technique is particularly useful for correlating microstructure with macroscopic properties without destroying the specimen. NASA datasets related to accelerated aging and damage evolution in composite materials enable the analysis of how structural performance is progressively modified by environmental and mechanical cycles [108]. These precedents are highly relevant to sustainable hybrid materials intended for space environments, where demonstrating high initial mechanical performance alone is insufficient; long-term stability must also be ensured under thermal cycling, vacuum, radiation, moisture exposure, abrasion, and mechanical loading.

3.10. Environmental Requirements and Validation for Space Applications

The transition of plant fibers and nanocellulose from laboratory-scale materials to space-qualified components requires a more rigorous validation sequence than conventional textile applications. The outer surface of a spacesuit must be evaluated for tensile strength, tear resistance, abrasion resistance, cut resistance, dimensional stability, thermal behavior, moisture uptake, radiation-induced degradation, and particle penetration resistance [1,109]. The need for such an approach is demonstrated by the MISSE-7 exposure tests, in which outer spacesuit fabrics remained in low Earth orbit for 18 months [32]. Following exposure, the integrated solar absorptance increased by 7%–38%, whereas fibers previously abraded with lunar dust simulant exhibited an approximately fourfold reduction in tensile strength and elongation at break, accompanied by an approximately twofold increase in elastic modulus [32,109,110]. These results demonstrate that relatively rapid changes in the optical and mechanical properties of textile materials can compromise their thermal and structural performance.

In addition to mechanical and environmental durability, flammability must be considered a primary qualification criterion for plant-derived materials intended for crewed spacecraft. NASA-STD-6001B Test 1 evaluates upward flame propagation under the worst-case combination of oxygen concentration, pressure, temperature, and material configuration, with self-extinguishment and flame-induced material transfer as failure criteria [111,112]. This is particularly relevant to cellulose-based materials because their combustion behavior is strongly influenced by the surrounding oxygen conditions [113]. Consequently, terrestrial flammability data cannot be directly extrapolated to crewed spacecraft, and untreated lignocellulosic fibers require specific testing under representative spacecraft conditions before their use in critical components can be considered.

Vacuum outgassing and atomic oxygen (AO) exposure represent additional constraints for space applications. ASTM E595 uses total mass loss and collected volatile condensable material as screening parameters, with historically used limits of $\leq 1.00\%$ and $\leq 0.10\%$, respectively [114]. Because cellulose-based materials are hygroscopic and can retain substantial amounts of moisture under ambient conditions, their moisture content and conditioning history should also be considered when evaluating the vacuum compatibility of the materials. Experimental evaluation of bamboo-derived cellulose nanofibers showed that the untreated CNF emitted only water, whereas bamboo and TEMPO-oxidized CNF produced additional volatile species, demonstrating the influence of composition and processing on vacuum compatibility [115]. For materials exposed to low-Earth orbit, AO can also induce surface degradation and mechanical-property losses. Exposure of high-modulus aramid fibers to 5 eV AO reduced tensile strength and Young's modulus to 65% and 53% of their initial values, respectively [116]. Therefore, untreated plant-derived materials should not be assumed to meet spacecraft material-screening requirements and should be specifically evaluated for vacuum outgassing and AO-induced degradation.

Lunar dust is one of the most critical tests for any candidate plant-based material. Tests conducted with spacesuit fabrics demonstrated that Kevlar, Orthofabric, and Tyvek exhibit different levels of resistance to lunar simulant penetration and abrasion, with Tyvek showing the lowest wear among the evaluated materials [117]. Subsequent dust-mitigation studies using carbon nanotube fibers demonstrated the ability to repel more than 80% of lunar simulant, indicating that surface coatings and architectures can substantially reduce particle–fabric interactions [118]. More recently, liquid-nitrogen spraying under vacuum achieved 98.4% removal of lunar simulant mass, including 95.9% of particles with diameters below 10 μm , under optimized conditions [119].

For plant-based fibers, these findings indicate that validation should not be limited to initial mechanical strength; particle retention, mass loss, changes in mechanical strength, changes in thermal conductivity, and surface degradation should be quantified following repeated exposure and cleaning cycles [120]. The NASA–ASTM collaboration is currently developing specific test methods for spacesuits and gloves, including regolith abrasion testing and evaluation of cut resistance under cryogenic conditions as low as 77 K [121]. Thus, a plant-based material could only be considered a space-qualified candidate after demonstrating performance comparable to the functional requirements of the intended component and maintaining stability following representative environmental exposure cycles.

3.11. Comparative Assessment of Conventional and Plant-Derived Spacesuit Materials

Table 6 shows the marked difference between the maturity of conventional spacesuit materials and the current evidence for plant-derived alternatives. Kevlar, Nomex, Vectran, and Spectra combine high tensile strength and relatively low density with documented testing under simulated or actual space environments, while Ortho-Fabric and β -cloth have additional LEO, lunar-dust, Apollo, and operational EMU heritage [28,122–124]. In comparison, flax, hemp, ramie, and bamboo exhibit useful tensile strength and low-to-moderate density, but their high moisture sensitivity and the absence of EVA/LEO validation remain important limitations [45,125–127]. Natural rubber, cotton, jute, and silk have also been investigated for radiation-shielding applications, with modeled effective-dose values of approximately $0.95\text{--}1.04\text{ mSv day}^{-1}$ under a defined shielding configuration; however, these results represent computational estimates rather than demonstrated radiation resistance in space [127]. Thus, although plant-derived materials can provide favorable mechanical and lightweight characteristics, their suitability for spacesuit applications cannot be established from tensile strength alone and requires validation against the combined effects of thermal cycling, radiation, atomic oxygen, abrasion, moisture, and long-duration space exposure.

Table 6. Comparative properties and space-environment validation of conventional and plant-derived materials for spacesuit applications.

Material	Function	Tensile Strength (MPa)	Density (g cm ⁻³)	Thermal Stability	Moisture Sensitivity	Radiation Evidence	Abrasion Resistance	Space Validation	Ref.
Kevlar	Structural reinforcement and mechanical protection	3600–4100	1.44	Decomposition ≈550 °C	Moderate	LEO/simulated exposure	High	NASA testing and flight heritage	[28,117,122]
Nomex	Thermal and flame protection	650	1.38	Decomposition ≈400 °C	Moderate	Simulated/LEO evaluation	Moderate–high	NASA testing and flight heritage	[28]
Vectran	Cut/abrasion protection; glove components	2850	1.4	Decomposition ≈400 °C	Very low	LEO/simulated exposure	High	Spacesuit use and NASA testing	[28,122,123]
Spectra (UHMWPE)	Structural/restraining components	2400	0.97	Limited; melting ≈150 °C	Very low	Space-environment testing	Very high	Spacesuit components	[28,122]
Ortho-Fabric	The outer protective layer	—	~1.4 *	Constituent-dependent	Low–moderate	LEO exposure	High; tested with lunar-dust	Operational EMU	[32,117]
Beta cloth	Thermal/environmental protection	—	~2.5 †	Very high	Very low	Orbital exposure	High	Apollo/LDEF heritage	[32,124]
Flax	Reinforcement/secondary textile	345–1830	1.5	~296–388 °C	High	No EVA/LEO data	No space-specific data	No operational validation	[45,128]
Hemp	Reinforcement/secondary textile	550–1110	1.5	~290–393 °C	High	No EVA/LEO data	No space-specific data	No operational validation	[45,128]
Ramie	High-strength reinforcement	400–938	1.5	~200 °C	High	No EVA/LEO data	No space-specific data	No operational validation	[45,125]
Bamboo fiber	Reinforcement/secondary textile	140–800	0.6–1.1	Strength loss >200 °C	High	No EVA/LEO data	No space-specific data	No operational validation	[115,126]
Natural rubber	Radiation shielding/flexible component	—	~0.92	Moderate	Low–moderate	0.950 mSv day ⁻¹ modeled	No space-specific data	Simulation only	[127]
Cotton	Secondary textile/radiation shielding	287–800	~1.5–1.6	Moderate	High	1.004 mSv day ⁻¹ modeled	No space-specific data	Simulation only	[127]
Jute	Reinforcement/secondary textile	393–800	~1.3–1.5	Moderate	High	1.036 mSv day ⁻¹ modeled	No space-specific data	Simulation only	[127]
Silk	Lightweight secondary textile	100–1500	~1.3	Moderate–high	Moderate	1.004 mSv day ⁻¹ modeled	No space-specific data	Simulation only	[127]

Note: EVA, extravehicular activity; LEO, low Earth orbit; EMU, extravehicular mobility unit; LDEF, long duration exposure facility. * Approximate density associated with the principal Ortho-Fabric constituents. † Approximate density of the Beta cloth glass-fiber substrate. Radiation values reported for natural rubber, cotton, jute, and silk correspond to modeled effective dose equivalents under a spacecraft shielding configuration consisting of 50 g cm⁻² of aluminum plus 20 g cm⁻² of the respective material, rather than to an isolated spacesuit layer. Silk is an animal-derived fiber and is included for comparative purposes. Information compiled and synthesized by the authors based on the cited references.

3.12. Plant Biodiversity as a Source of Novel Fibers and Biomaterials

The Amazonian biodiversity of Peru and Brazil expands the range of plant resources that can be investigated for developing sustainable fibers, biomaterials, and composites intended for advanced applications (Table 7). Among species with experimental evidence of interest for materials engineering, *Attalea speciosa* stands out, with fibers exhibiting diameters ranging from 0.18 to 0.47 mm, densities of 0.27–0.79 g cm⁻³, tensile strength of up to 100.76 MPa, and an elastic modulus of up to 6.33 GPa [129,130]. Chemical characterization revealed 37.97% cellulose, 32.34% hemicellulose, and 28.53% lignin, while the crystallinity index reached 81.06% and the microfibrillar angle was approximately 7.67°, parameters associated with reinforcing capability in polymer composites [130]. *Mauritia flexuosa* also exhibits potential for lightweight material applications: fiber characterization studies demonstrated thermal stability up to approximately 200 °C, a relatively small lumen, and thick cell walls [131]. In addition, *M. flexuosa* fiber-reinforced composites exhibited flexural strength of up to 253.7 MPa, although fiber–matrix adhesion was identified as a limitation [131]. These findings indicate that Amazonian species may provide structural fibers and feedstocks for porous architectures, reinforcements, and low-density hybrid materials.

Other Amazonian resources exhibit characteristics that justify their use as platforms for bio-based materials. For example, *Manicaria saccifera* fibers exhibited a crystallinity index of 60.6%, thermal stability up to approximately 264 °C, an apparent density of 0.97 g cm⁻³, and a breaking load of 432 N for the natural fibrous tissue [132]. In another study, individual fibers of this species exhibited a Young's modulus of 9.51 ± 4.38 GPa and a tensile strength of 68.62 ± 27.93 MPa, together with high biocompatibility [133]. The corresponding coefficient of variation for tensile strength is approximately 41%, indicating substantial dispersion relative to the mean value. This variability illustrates why individual-fiber tensile strength should be interpreted as an indicator of material potential rather than as a directly transferable design value for spacesuit textiles. For aerospace applications, statistically based mechanical allowables and reproducibility assessments are required before such fibers can be considered for structural or protective components. For *Euterpe oleracea*, fibers obtained from the mesocarp and seed exhibited thermal stability up to approximately 230 °C under an inert atmosphere and an irregular surface associated with the presence of parenchyma cells [134]. *Carapa guianensis* has a relevant fibrous architecture in its wood, with a mean fiber length of 1505.27 µm in upland trees, a cell-wall thickness of 3.73 µm, density of 0.52 g cm⁻³, and a microfibrillar angle of 11.31° [135].

Copernicia prunifera exhibits high crystallinity (86.9%), a low microfibrillar angle (7.48°), tensile strength of 205–264 MPa, Young's modulus of 8.2–9.2 GPa, and elongation at break of 1.7%–2.6%, together with an onset of thermal degradation near 267 °C [136–138]. This combination of strength, stiffness, and thermal stability indicates the potential of lignocellulosic reinforcement in lightweight biocomposites, particularly in semistructural components, support layers, or protective elements where mass reduction is required while maintaining mechanical capability. However, its incorporation into systems intended for spacesuits would require the optimization of the fiber–matrix interface and validation of its behavior under vacuum, thermal cycling, radiation, and abrasion.

A relevant processing constraint emerges from the thermal stability of the reported fibers compared with matrices suitable for high-temperature aerospace applications. The reported thermal stability/degradation temperatures of *Mauritia flexuosa* (≈200 °C), *Euterpe oleracea* (≈230 °C), *Manicaria saccifera* (≈264 °C), and *Copernicia prunifera* (≈267 °C) are below the processing temperatures reported for high-temperature polymer matrices, including phenylethynyl-terminated polyimides, which require curing above 350 °C [139],

polyether ether ketone, typically processed at approximately 380–410 °C [140], and polyphenylene sulfide, commonly melt-processed at approximately 300–340 °C [141]. In contrast, the composites reported for the Amazonian fibers considered here employ polylactic acid, epoxy resin, and polypropylene, which involve less severe processing conditions than these high-temperature matrices [129,139–141]. This difference is critical because exposure of lignocellulosic fibers to elevated processing temperatures can cause chemical and structural degradation, reducing fiber strength and potentially compromising fiber–matrix interfacial performance [142]. Therefore, the reported feasibility of these fibers in polylactic acid, epoxy resin, and polypropylene-based composites cannot be directly extrapolated to high-temperature aerospace matrix systems; their integration into such systems would require compatible processing windows or alternative manufacturing strategies that limit thermal exposure.

These findings indicate that the Amazonian biodiversity contains materials with diverse combinations of crystallinity, thermal stability, density, cellular architecture, and mechanical performance; however, their use in spacesuits remains hypothetical. The main challenge is translating these naturally occurring characteristics into engineered materials capable of maintaining performance under vacuum, thermal cycling, radiation, abrasion, and extraterrestrial regolith exposure.

Table 7. Structural and functional properties of Amazonian plant resources with potential for use in space-material applications.

Plant Resource	Property	Structural/Chemical Characteristic	Potential of the Space Materials	Main Limitation	Ref.
<i>Attalea speciosa</i>	Tensile strength: 100.76 MPa; modulus: 6.33 GPa	Crystallinity: 81.06%; microfibrillar angle: 7.67°	Biocomposite reinforcement	Structural variability	[129,130]
<i>Mauritia flexuosa</i>	Biocomposite flexural strength: 253.7 MPa; thermal stability ≈200 °C and thick cell walls	Relatively small lumen	Lightweight biocomposites	Fiber–matrix adhesion	[131]
<i>Manicaria saccifera</i>	Young's modulus: 9.51 ± 4.38 GPa; tensile strength: 68.62 ± 27.93 MPa; thermal stability ≈264 °C	Crystallinity: 60.6%;	Reinforcement and biotextiles	Lack of space-environment validation	[132,133]
<i>Euterpe oleracea</i>	Thermal stability ≈230 °C	Irregular surface; lignocellulosic structure	Composite materials	Environmental sensitivity	[134]
<i>Carapa guianensis</i>	Fiber length: 1505.27 µm; density: 0.52 g/cm ³	Cell wall thickness: 3.73 µm; microfibrillar angle: 11.31°	Structural biomaterials	Data corresponding to wood rather than isolated textile fibers	[135]
<i>Copernicia prunifera</i>	Tensile strength: 205–264 MPa; young's modulus: 8.2–9.2 GPa; elongation: 1.7%–2.6%; onset of degradation ≈267 °C	Crystallinity: 86.9%; microfibrillar angle: 7.48°; cellulose: 20.2%	Reinforcement of the lightweight structural biocomposites	Requires validation under space conditions	[136–138]

Note: Information compiled and synthesized by the authors based on the cited references.

3.13. Extraterrestrial Dust Contamination as a Challenge for Sustainable Materials Development

Extraterrestrial dust contamination represents a critical challenge for alternative materials intended for use in spacesuits (Figure 5). During the Apollo missions, problems associated with contamination, abrasion, mechanism obstruction, thermal control, sealing, and particle inhalation were identified [110]. In Apollo spacesuits, 80% of the particles collected from the external surface of Apollo 17 corresponded to lunar soil, with a mean diameter of approximately 10.5 µm, which could cause Teflon fiber separation and fraying [34]. Dust can also be transported into spacecraft, increasing the exposure of astronauts [143]. Experiments with nanomaterial-reinforced functional textiles demonstrate that hybrid strategies can improve the durability of textile structures, as observed in carbon nanotube-based sensors subjected to 60 flexion–extension cycles and nylon yarns containing silver nanoparticles that maintained their conductivity after 30

washing cycles [144]. These results may guide combinations of plant-derived fibers with high-performance components, which should provide abrasion resistance, low particle retention, thermal stability, and durability following dust exposure.

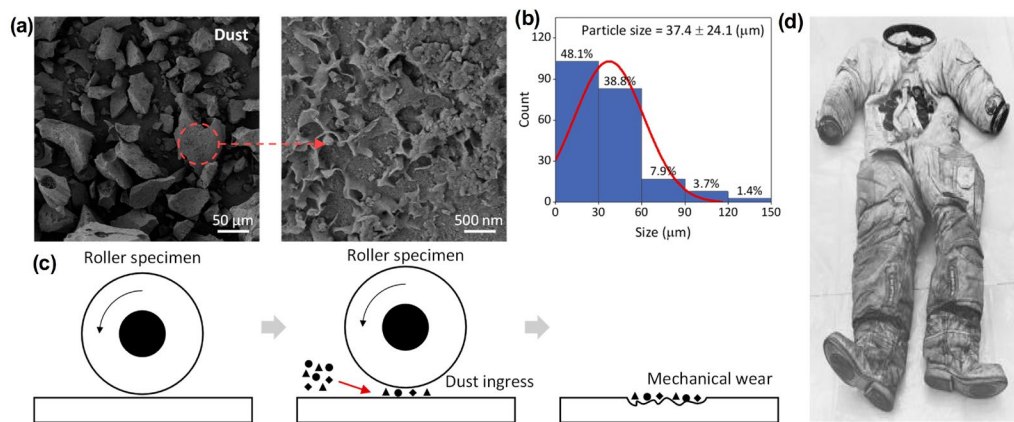


Figure 5. Particle-size distribution of lunar dust and its morphological characteristics relevant to textile-material contamination. (a) SEM characterization of lunar dust; (b) particle-size distribution; (c) schematic illustration of mechanical wear; and (d) lunar dust-covered spacesuit. Adapted from Zhang et al. [145], under a Creative Commons Attribution (CC BY 4.0) license.

The particle-size distribution of lunar dust spans a broad range of sizes, concentrated primarily in the tens-of-micrometers scale, with a mean diameter of $37.4 \pm 24.1 \mu\text{m}$ (Figure 5). Particles smaller than $30 \mu\text{m}$ account for approximately half of the population, whereas those below $60 \mu\text{m}$ predominate in the distribution [146]. This multiscale distribution is relevant to fibrous materials because fine particles can deposit on textile surfaces and penetrate the pores, interstices, and interfaces between layers. Consequently, the surface and internal architecture of fibers should be considered when developing sustainable materials for extraterrestrial environments, particularly about particle retention, abrasion, and structural integrity. This issue is particularly relevant in plant-derived fibers because of their porous structure and the potential interaction between dust particles and surface irregularities. Therefore, coatings, hybrid architectures, and surface modifications could be investigated to reduce particle adhesion and penetration while simultaneously maintaining the mechanical and thermal properties required for space applications.

3.14. Plant-Inspired Principles in Multifunctional Spacesuits

The incorporation of bioinspired functions into spacesuits should consider the quantitative requirements of current systems. EVA suits must regulate pressure, temperature, atmospheric composition, and heat removal, while metabolic heat generation can impose substantial thermal-management demands during suited operations [29,30]. Therefore, plant mechanisms of thermal adaptation and phase-change materials may inspire passive or complementary thermal-management strategies [147]. However, the proposed solutions should provide measurable benefits without increasing mass, volume, energy consumption, or system complexity.

Plant-inspired principles are more directly relevant to thermal regulation, material architecture, and multifunctional surfaces than to biological atmospheric regeneration. Although microalgae have been investigated for oxygen production and life-support applications, these systems are more suitable for habitats or dedicated life-support modules than for spacesuit textile integration [29,148–150]. Therefore, their relevance to spacesuit materials remains limited. Instead, plant biomass could be valorized as a source of functional materials and bioactive compounds [72,151].

The spacesuit architecture also offers opportunities for bioinspired innovation. Conventional cooling garments rely on extensive tubing for water circulation [152], whereas the BioSuit concept uses mechanical counterpressure and a “second-skin” architecture to reduce bulk and improve mobility [153]. Combined with plant-inspired morphological adaptation and thermal regulation, such approaches could support multifunctional and more efficient spacesuit architectures. However, their simultaneous integration has not yet been experimentally demonstrated, highlighting the need for hybrid systems with verifiable technical advantages.

4. Research Gaps and Future Perspectives for Sustainable Spacesuits

4.1. Research Landscape and Knowledge Gaps

The keyword co-occurrence network in Figure 6 identifies interconnected research themes involving “cellulose”, “cellulose nanofibril”, “nanofibers”, “aerogels”, “thermal insulation”, “thermal conductivity”, “protective clothing”, and “flame retardants”. These associations indicate that the retrieved literature addresses cellulose-based materials, fibrous and porous structures, thermal management, and protective textile functionality. However, keyword co-occurrence reveals thematic relationships rather than technological readiness or direct applicability to spacesuits. The presence of “protective clothing” and “flame retardants” alongside cellulose-related terms does not demonstrate that bio-based materials have been validated against aerospace safety requirements. Accordingly, the network should be interpreted as a representation of the main thematic connections in the retrieved literature rather than as evidence of established applications in spacesuit systems.

The principal research gap concerns the limited evidence linking these material-related themes to the combined performance requirements of spacesuits, including low mass, mechanical integrity, flexibility, thermal protection, abrasion resistance, dimensional stability, and environmental durability [1]. Although cellulose-based nanostructures and porous materials may offer opportunities for developing lightweight functional components, their suitability cannot be established from individual properties or bibliometric associations alone [53]. Future research should quantify the relationships between material composition, processing, structure, and performance under application-relevant conditions, particularly regarding the retention of mechanical and thermal properties following environmental exposure and repeated deformation. This approach would help distinguish promising material concepts from experimentally validated solutions and determine whether the material concepts represented in Figure 6 could provide measurable benefits in future sustainable spacesuit architectures.

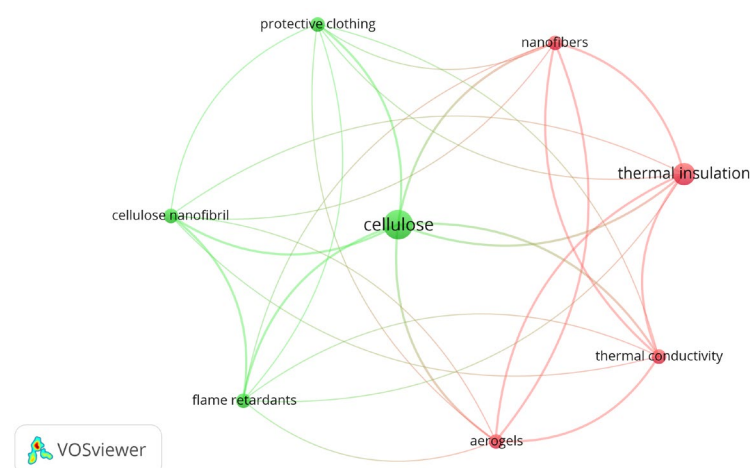


Figure 6. Keyword co-occurrence network of the retrieved literature. VOSviewer version 1.6.19 was used to generate the visualization based on publications retrieved from the Scopus database,

without publication-year restrictions, to identify the main thematic connections in the literature. The following search query was applied: (spacesuit OR “space suit” OR “extravehicular mobility unit” OR “extravehicular activity” OR “intravehicular activity”) AND (“bio-based material” OR “natural fiber” OR lignocellulos* OR cellulose OR nanocellulose OR bio-composite). Node size represents the occurrence of each keyword, links indicate co-occurrence relationships, and colors distinguish thematic clusters. Original figure developed by the authors.

4.2. Cellulose-Based Nanofibers and Aerogels for Thermal Insulation

The associations among “cellulose”, “cellulose nanofibril”, “nanofibers”, “aerogels”, and “thermal insulation” identify lightweight fibrous and porous materials as potential candidates for further investigation. Cellulose-based nanostructures and aerogels may offer opportunities to engineer low-density materials with tailored thermal properties; however, low density and favorable insulation performance do not necessarily translate into adequate mechanical reliability. Porosity, fiber morphology, moisture sensitivity, interfacial interactions, and processing conditions may affect thermal conductivity, compressive resistance, dimensional stability, and recovery after deformation [154]. Future studies should therefore characterize thermal and mechanical properties simultaneously and determine how these properties change following repeated compression, bending, abrasion, and thermal cycling.

A further limitation is the potential discrepancy between the performance of isolated specimens and that of integrated textile assemblies [155]. Layer thickness, compression, interfaces, and manufacturing processes can modify heat transfer and mechanical behavior, making material-level measurements insufficient to establish spacesuit suitability. Candidate nanofibers and aerogels should consequently be evaluated in representative multilayer configurations and compared with conventional aerospace insulation materials under equivalent functional requirements. Their potential value should be established through measurable improvements in thermal performance, mass, durability, or environmental impact rather than inferred from their bio-based origin or porous structure alone.

4.3. Protective Clothing and Flame-Retardant Functionality

The association of “protective clothing”, “cellulose”, and “flame retardants” identifies protective textile functionality as a relevant research direction. Nevertheless, the network does not demonstrate that cellulose-based materials meet the fire-safety or broader protective requirements of spacesuits. Future investigations should determine whether flame-retardant treatments can provide adequate flame resistance while maintaining tensile and tear strength, flexibility, low mass, and compatibility with adjacent textile layers. The chemical composition of these treatments should also be considered because additional processing, potentially hazardous constituents, or reduced end-of-life compatibility may offset some of the expected sustainability benefits [156].

Initial flame-resistance measurements are insufficient to establish long-term performance. Abrasion, repeated deformation, thermal exposure, and environmental aging may alter coating integrity or reduce treatment effectiveness. Accordingly, studies should quantify functional retention after repeated exposure and assess whether degradation affects the underlying substrate or the integrity of the multilayer assembly. Flame resistance must also be distinguished from resistance to vacuum, radiation, thermal cycling, and particulate abrasion [1]. The practical relevance of these materials will depend on demonstrating that the intended protective functions can be maintained under the specific conditions associated with their intended use.

4.4. Environmental Durability and Multilayer Integration

The transition from laboratory-scale materials to spacesuit components requires evidence of property retention under relevant environmental and mechanical stresses [1]. Vacuum exposure, radiation, thermal cycling, repeated deformation, and abrasive particles may alter fiber structure, surface chemistry, interfacial adhesion, and protective treatments. Future experimental programs should quantify these changes using controlled exposure protocols and, where technically justified, combined-stress testing. Such approaches are necessary because isolated tests may not capture interactions between environmental degradation and mechanical loading, potentially leading to overestimation of service life.

Integration into multilayer architectures introduces additional uncertainties associated with interfacial adhesion, stiffness mismatch, thermal expansion, delamination, and changes in flexibility or thermal performance [157]. Cellulose-based fibers, nanofibers, and aerogels should therefore be assessed not only as individual materials but also within representative textile assemblies and components. A hierarchical validation strategy, progressing from material characterization to fabric and component testing, would help determine whether laboratory-scale advantages persist after manufacturing and integration [158]. Until such evidence is available, the application of these materials in spacesuit components should be regarded as a prospective research direction rather than a demonstrated engineering solution.

4.5. Research Priorities and a Validation Roadmap

The research gaps identified in the preceding sections indicate the need for a staged validation strategy for cellulose-based materials intended for potential spacesuit applications. Initial studies should establish reproducible material properties, including thermal behavior, mechanical integrity, dimensional stability, and resistance to environmental aging [154]. Subsequent investigations should evaluate property retention after repeated deformation, abrasion, thermal cycling, and other application-relevant exposures. Promising candidates should then be incorporated into representative textile assemblies to determine whether their material-level advantages persist after manufacturing and integration.

Progression toward component-level evaluation should depend on measurable performance against predefined engineering requirements rather than on bio-based content or isolated laboratory results. This approach would help prioritize materials with demonstrable functional benefits, identify critical failure mechanisms, and establish the evidence required for subsequent qualification studies. Environmental, economic, and social sustainability should be assessed alongside this validation process, as discussed in Sections 4.6–4.8.

4.6. In-Space Manufacturing, Repair, and Material Circularity for Long-Duration Missions

Material circularity should be treated as a core design criterion for spacesuits intended for long-duration lunar and Martian missions. Replacing conventional aerospace fibers with terrestrial bio-based materials does not, by itself, establish a significant sustainability advantage because feedstock production, material processing, qualification, transportation, and launch remain part of the overall resource and logistics burden. A more robust approach is therefore to integrate modularity, design for disassembly, repairability, and material recovery into the suit architecture. Reversible joining systems, compatible material families, and replaceable textile layers, coatings, and protective components could enable component-level maintenance and refurbishment while reducing premature disposal of the complete suit. The benefits of these strategies should be evaluated in relation to material lifetime,

maintenance frequency, resupply requirements, energy consumption, and end-of-life recovery.

In-space manufacturing could further support this approach by enabling the fabrication or refurbishment of selected textile and polymeric components from feedstocks available within mission infrastructure [159]. In this context, plant-derived materials could be investigated not only as terrestrial alternatives to synthetic fibers but also as potential feedstocks for producing polymers, fibers, coatings, foams, or composite matrices within partially closed material cycles. However, the extraterrestrial production and qualification of plant-derived materials for spacesuit applications remain prospective and have not been demonstrated as an integrated process. Future research should therefore examine the feasibility of the entire chain, from biomass cultivation and feedstock conversion to material processing, component fabrication, environmental qualification, repair, reuse, and material recovery. The relevant sustainability objective would be to reduce dependence on Earth-derived supplies, material losses, energy demand, and waste generation through circular and partially autonomous material systems [160].

4.7. Assessment of Life Cycles and Sustainability Trade-Offs

A bio-based origin does not inherently guarantee a lower environmental impact [161]. For spacesuit applications, sustainability must be assessed across the entire life cycle, including feedstock production, processing, functionalization, manufacturing, transportation, maintenance, service life, and end-of-life management. For natural fibers and lignocellulosic feedstocks, this assessment should explicitly account for the environmental burdens associated with extraction, fiber separation, washing, alkaline treatment, bleaching, drying, chemical modification, and subsequent processing into yarns, fabrics, composites, or other textile structures.

Future life-cycle assessment (LCA) studies should integrate environmental indicators with engineering parameters such as mass per unit area, specific strength, durability, thermal stability, repairability, and property retention after aging. This integrated assessment is necessary to identify potential trade-offs between environmental performance and the additional processing or reinforcement required to achieve aerospace-level functionality.

Chemical functionalization, crosslinking, nanoparticle incorporation, protective coatings, hybridization with synthetic polymers, and repeated maintenance may increase energy consumption, material inputs, or environmental burdens [162]. Consequently, future assessments should distinguish the environmental impacts of the original feedstock from those of the complete material system required to achieve the target performance. This distinction could reveal cases in which a material with a high bio-based content provides limited sustainability benefits after extensive modification, reinforcement, or repeated replacement over its service life.

Quantitative life-cycle evidence illustrates the importance of considering processing-related impacts. For example, a recent LCA of lignocellulosic aerogels identified cellulose extraction and alcogel preparation as major environmental hotspots, while process upscaling was estimated to reduce greenhouse-gas emissions by 87%–92% and acidification impacts by 75%–87% [163]. Similarly, an LCA of a garment containing chemically recycled cellulose fiber reported a climate impact of approximately 22 kg CO₂-eq per garment, with cradle-to-gate processes representing approximately 77% of the total impact [164]. The systematic application of LCA in the space sector remains relatively recent, although its use is increasing as a tool for sustainable design and environmental assessment, including studies conducted according to the ISO 14040/14044 framework [165–167]. Available space-sector studies also

show heterogeneous system boundaries, functional units, and methodological approaches [168].

These terrestrial results should therefore be considered indicative rather than directly transferable to spacesuit textiles. Future assessments should compare plant-derived materials with conventional spacesuit materials using application-specific functional units, such as kg CO₂-eq per m² of qualified textile or per mission-year. Comparisons should also account for mass, mechanical and thermal performance, durability, radiation resistance, vacuum compatibility, outgassing, abrasion, maintenance, and replacement frequency.

4.8. Ecological, Economic, Social, and Regulatory Dimensions of Sustainable Development of Spacesuits

The sustainability of bio-based spacesuit materials should be demonstrated through a life-cycle perspective rather than inferred from their renewable origin. A state-of-the-art assessment of environmental LCA in the space sector identified 38 relevant documents and showed that the available case studies present highly heterogeneous goal and scope definitions, life-cycle inventories, and impact assessment approaches. This heterogeneity limits the comparability of environmental results and reveals methodological gaps in the application of LCA to the space industry [168]. More recent life-cycle sustainability assessment (LCSA) research recommends indicators including global warming potential, ozone depletion, ionizing radiation, toxicity, land and water use, resource consumption, and primary energy demand [169]. These indicators are relevant to cellulose-based spacesuit materials because environmental burdens may shift from fossil feedstocks toward cultivation, alkaline treatment, bleaching, functionalization, nanoparticle incorporation, transportation, and replacement. Assessments should therefore use functional units related to spacesuit performance, such as kg CO₂-eq per m² of qualified textile or environmental burden per mission-year, while accounting for processing, durability, replacement, and end-of-life management [170,171].

The economic and social dimensions should be evaluated alongside environmental performance because aerospace qualification may require specialized processing, testing, manufacturing, maintenance, and replacement. The proposed LCSA framework for space activities includes indicators such as total cost of ownership, production cost, operating cost, and cost efficiency, together with social indicators covering worker health and safety, fair wages, human rights, discrimination, and occupational accidents [169]. Quantitative results from the MİOS mission case study illustrate the scale of these dimensions: its baseline design was associated with approximately 1.12×10^7 kg CO₂-eq for climate change, 2.58×10^5 kg Sb-eq for mineral resource depletion, and a whole-life cost of approximately €1.19 × 10⁸ in 2000 euros [171]. Labor represented €6.89 × 10⁷, followed by launch activities at €3.61 × 10⁷ and transportation at €9.30 × 10⁶ [171]. Although these values are specific to the mission scenario and cannot be directly transferred to spacesuit materials, they illustrate the importance of manufacturing, labor, logistics, and operational costs in overall sustainability assessments. For bio-based spacesuit textiles, relevant considerations include processing complexity, occupational exposure, repair labor, replacement frequency, supply-chain traceability, and service life [169].

The regulatory dimension requires sustainability considerations to be integrated with existing technical and crew-safety qualification requirements. The 21 UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities address regulatory, operational, safety, scientific, and international cooperation aspects, but do not establish material-specific sustainability or qualification criteria for spacesuit textiles [172]. At the engineering level, NASA-STD-6001B addresses material flammability, outgassing, and compatibility, illustrating the importance of safety and performance testing in material qualification. These requirements do not, by themselves, establish compliance with life-

cycle environmental, social, or circularity criteria [112]. Recent work on space sustainability also argues for extending conventional approaches to include circular material strategies involving longer service life, repair, reuse, and material recovery [170]. Future qualification frameworks for sustainable spacesuit materials could consequently incorporate measurable criteria for material traceability, restricted substances, contamination control, environmental impact, repairability, recyclability, and end-of-life management, while retaining mechanical, thermal, chemical, and crew-safety requirements as mandatory constraints [169,170]. Such an approach would enable ecological performance, economic viability, social responsibility, circularity, and technical reliability to be evaluated within a common framework rather than treated as independent sustainability claims.

5. Conclusions

The evidence reviewed indicates that plant biodiversity provides a promising but still underdeveloped source of fibers, cellulose-based materials, and bioinspired strategies for sustainable space textiles. Plant fibers, such as flax, hemp, and ramie, exhibit specific mechanical properties, whereas nanocellulose, cellulose aerogels, functionalized substrates, and bio-based composites offer potential for reinforcement, insulation, barrier, and multifunctional applications. However, their performance strongly depends on structure, processing, and functionalization, and comparison with high-performance fibers such as Kevlar 49 indicates that plant-derived fibers cannot currently replace critical spacesuit materials. Therefore, their most realistic near-term role is within selective hybrid and multilayer architectures.

Functionalization and material engineering can improve properties such as interfacial adhesion, hydrophobicity, dimensional stability, and electromagnetic shielding, but these benefits must be balanced against processing complexity and fiber integrity degradation. Accordingly, plant-derived materials may be considered for secondary reinforcement, insulation, membranes, coatings, and multifunctional layers, while qualified high-performance materials remain necessary for critical pressure retention and external protective functions. The main research gap is the limited validation of these materials under combined space-relevant conditions, as most reported results were obtained under terrestrial laboratory conditions.

Accordingly, future research should prioritize standardized component-level testing under vacuum, thermal cycling, radiation, abrasion, mechanical fatigue, and lunar or Martian regolith exposure, together with dimensional stability, interfacial degradation, and long-term property retention. Modularity, repairability, material recovery, and potential in-space manufacturing should also be investigated. Thus, plant-derived and bioinspired materials should currently be regarded as complementary rather than substitutive resources, with their integration into spacesuit systems dependent on demonstrating reproducible performance, environmental stability, and safety under representative space conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AO	Atomic Oxygen
ASTM	American Society for Testing and Materials
CNF	Cellulose Nanofibrils
CNC	Cellulose Nanocrystals
EMI	Electromagnetic Interference
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
ISO	International Organization for Standardization
IVA	Intravehicular Activity
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
micro-CT	Micro-computed X-ray Tomography
NASA	National Aeronautics and Space Administration
TMG	Thermal Micrometeoroid Garment
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UV	Ultraviolet

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